

Measurement of the Atmospheric ν_e flux in IceCube

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We report the first observation in a high energy neutrino telescope of cascades induced by atmospheric electron neutrinos and by neutral current interactions of atmospheric neutrinos of all flavors. Using data recorded during the first year of operation of IceCube's DeepCore low energy extension, a sample of 1029 events is observed in 281 days of data. The number of observed cascades is $N_{\text{cascade}} = 496 \pm 66(\text{stat.}) \pm 88(\text{syst.})$ and the rest of the sample consists of residual backgrounds due to atmospheric muons and charged current interactions of atmospheric muon neutrinos. The flux of the atmospheric electron neutrinos is determined in the energy range between approximately 80 GeV and 6 TeV and is consistent with models of atmospheric neutrinos.

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The spectrum of atmospheric ν_μ (we do not differentiate between $\bar{\nu}$ and ν here) has been measured at energies up to 400 TeV [1]. Much less is known about atmospheric ν_e . These electron neutrinos come mostly from the decays of kaons and muons produced in cosmic-ray air showers. Underground water Cherenkov telescopes like IMB-3 and Super-Kamiokande as well as calorimetric detectors such as Fréjus, NUSEX, and Soudan-2 have studied atmospheric ν_e with energies up to a few tens of GeV [2–6], but no measurement has been made at higher energies. So far, searches for ν_e at higher energies have yielded upper limits [7–10]. Theoretical flux calculations for atmospheric ν_e are poorly constrained at energies above 100 GeV due to the uncertainties in kaon

production [11, 12].

Atmospheric neutrinos with energies below 100 GeV are of particular interest for studies of neutrino oscillations. The first oscillation maximum for $\nu_\mu \rightarrow \nu_\tau$, and corresponding minimum in the ν_μ survival probability, occurs at 24 GeV for vertically upward-going neutrinos [13]. More energetic atmospheric ν_e are an important no-oscillation baseline for comparison with lower energies, and are also an irreducible background for charm-induced and astrophysical neutrino searches.

In this Letter, we report on a measurement of atmospheric neutrino-induced cascades using the DeepCore infill array in IceCube. Here, the “cascades” refer to ν_e charged current (CC) interactions and neutral cur-

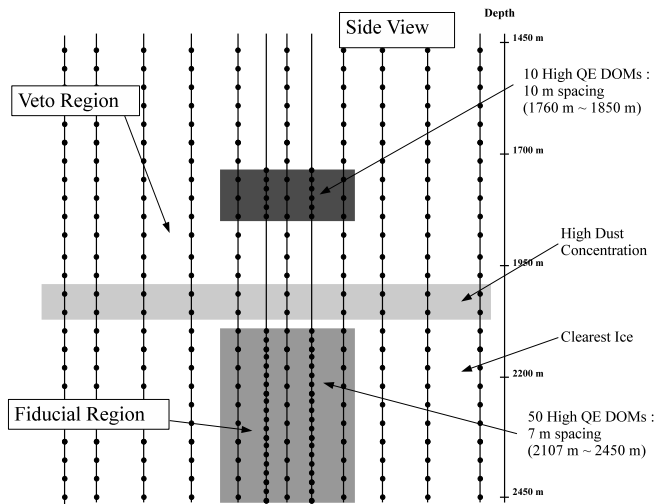


FIG. 1. Schematic side view of IceCube. The DeepCore infill array is shown in the shaded region.

rent (NC) interactions of neutrinos of all flavors. From a selected sample of cascade candidate events, an atmospheric ν_e flux is obtained in the energy range between about 80 GeV and 6 TeV.

IceCube is a high-energy neutrino detector buried in the Antarctic ice. It observes Cherenkov light from neutrino interactions. The main detection signatures for neutrinos are long, straight tracks and approximately spherical cascades. The former are created by neutrino-induced muons while the latter are produced by neutrino-induced electromagnetic and/or hadronic showers. The DeepCore infill array [14] to IceCube reduces the energy threshold of IceCube to energies as low as 10 GeV. DeepCore’s denser optical module spacing, higher quantum efficiency photomultiplier tubes, and lower trigger threshold, along with its deployment in the ice with the best optical properties in the lower half of the IceCube detector, all enhance low-energy neutrino detection.

This analysis used the first IceCube data run with DeepCore, from June 2010 to May 2011 when a total of 79 IceCube strings, including six specialized DeepCore strings, were operational. Each string consists of 60 digital optical modules (DOMs), equipped with a photomultiplier tube [15] and data acquisition electronics [16]. The DeepCore fiducial volume included these six strings and the seven adjacent standard IceCube strings. Since then, the remaining seven IceCube strings have been deployed, including two additional DeepCore strings. The schematic view of IceCube is shown in Fig. 1.

The DeepCore fiducial volume contains the 454 DOMs deployed at depths greater than 2100 m on the 13 strings of DeepCore. A dedicated DeepCore trigger was run on these DOMs. It read out the full IceCube detector if photons (“hits”) were observed in local coincidence (LC) on at least three neighboring DOMs within $2.5 \mu\text{s}$. Details of the LC circuitry are available in Ref. [16]. The average

trigger rate was 185 Hz and was a factor 13 smaller than the total IceCube trigger rate.

To avoid observational bias, 10% of the data, distributed evenly through the year, were used to develop the analysis and verify the detector simulation. The results presented here are based on the remaining 90% of the data set. After application of general data quality criteria, the 281 live-days of data that remain are used in this analysis.

To observe cascades, one must reject two types of backgrounds which are more numerous than the desired signal. The first class of background is muons produced in cosmic-ray air showers in the Earth’s atmosphere (“atmospheric muons”), which penetrate the 2100 m of ice above DeepCore and produce hits in the fiducial volume. The second class, much less common than the first, consists of atmospheric ν_μ also produced in air showers, which undergo CC interactions in the ice but which produce relatively low energy muons. Simulated data are obtained from Monte Carlo (MC) programs modeling the detector response to both of these types of background, as well as neutrino-induced cascades. An extensive air shower simulation [17] is used for atmospheric muons and a separate program [18] is for neutrinos weighted with the Honda [11] and the Bartol [19] atmospheric flux predictions. Selection criteria are applied to the data to reduce these backgrounds sufficiently to observe cascades. Fig. 2 compares the performance of these criteria with the predicted performance.

Following the trigger, an online veto algorithm identifies events where at least one LC hit is observed in the IceCube veto region (i.e., all IceCube sensors outside the fiducial region). If the times of the veto hits relative to the hits in the fiducial volume are consistent with a relativistic particle traveling through the veto region to DeepCore, the event is rejected [14]. This filter reduces the rate of atmospheric muons in DeepCore by a factor of 11 with respect to the DeepCore trigger, with negligible losses of neutrino interactions within the fiducial volume. An additional trigger criterion is applied in software, considering not only the LC hits but also non-LC hits which are not too isolated in time or space from other hits in the event. The trigger demands at least eight hits in the event, of which at least four must be in the fiducial volume.

Next, five variables quantifying the event topology are calculated. These are the depth of the first hit in the event, the sphericity of the event (the ratio of the smallest eigenvalue to the sum of all eigenvalues, the analogue of the tensor of inertia obtained by treating each hit as a point mass), the fraction of the total number of photoelectrons which are recorded within the first 600 ns (i.e., a measure of how fast the event develops), a similar fraction calculation excluding the two earliest hits assuming they may be due to noise, and the number of hits occurring in the veto region regardless of their time

or location. These variables are used to train a boosted decision tree (BDT) [20]. A cut on this 5-variable BDT reduces the number of data events to 2.7×10^6 , a factor of 1660 reduction from the DeepCore trigger. The number of predicted atmospheric cascades is 2.3×10^4 at this stage.

More computationally intensive event reconstruction algorithms are run over the surviving events, successively reconstructing the events under the hypotheses that they are produced by atmospheric muons or by neutrino-induced cascades. These likelihood-based reconstructions take into account the details of Cherenkov light propagation in the ice [21]. A second BDT is then trained to discriminate between atmospheric muons and cascades, using seven variables: the ratio of the best-fit likelihoods obtained from these reconstructions, the depth of the first hit, the horizontal distance of the first hit from the center of DeepCore, the fraction of the total number of photoelectrons detected within the first 300 ns, and variables measuring whether the hit pattern tends to drift across the detector during the event, indicative of a muon-like track through the detector rather than a spherically expanding light pattern which is a typical signature of a cascade. The numbers of events passing a cut on the second BDT are 3.8×10^4 (data), 2.1×10^4 (atm. μ), 1.7×10^4 (atm. ν_μ CC), and 9.6×10^3 (atm. cascades).

The data surviving this second BDT cut primarily consist of neutrino events, but the majority are produced by ν_μ CC interactions rather than cascades produced by ν_e or ν_μ NC interactions. Most of these ν_μ CC events come from neutrinos interacting within the DeepCore volume. The hadronic cascade produced at the neutrino interaction vertex may obscure the muon track emanating from the vertex unless the muon has sufficient energy to travel a considerable distance and is oriented such that it does not escape the detector volume undetected.

To reduce this ν_μ CC background, we apply several additional criteria. We require that the reconstructed neutrino interaction vertex of the event not be near the top or bottom of the fiducial volume, where a muon track could be missed if it escapes into the uninstrumented ice below the detector or the relatively dusty ice above DeepCore, and that the first hit in the event also fall in this volume. We further require that the best-fit cascade likelihood be both relatively good and also better than that obtained from the track fit, that enough DOMs were hit in the event that the comparison between these fits should have discrimination power, and finally we require a high value for a high signal efficiency from the second, 7-variable BDT [22].

A total of 1029 events pass all of these criteria. We estimate from simulation that about half of these events are residual backgrounds due to atmospheric muons (14%) and ν_μ CC events (36%). The remainder are ν_e and ν_μ NC events (inseparable from ν_e). The MC predicts

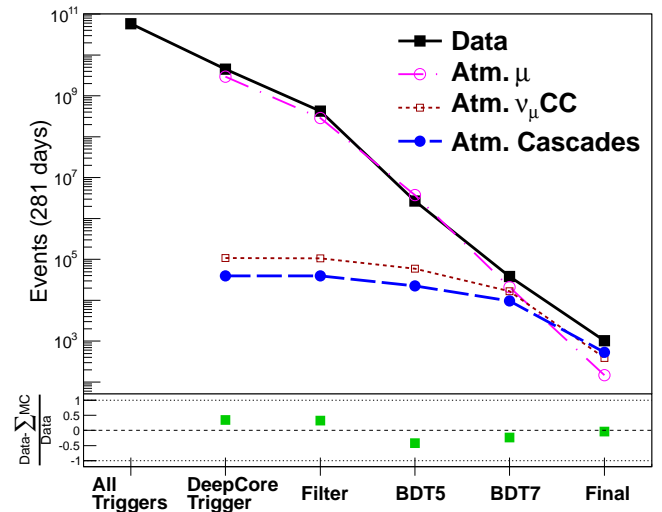


FIG. 2. (Color online) The number of data events (black filled squares) passing each selection criteria is shown with the MC predictions: atmospheric muon (magenta open circles), atmospheric ν_μ CC (red open squares), and cascade signal (blue filled circles). From left to right on the horizontal axis: all triggered events, DeepCore triggered events, DeepCore filtered events, 5-variable BDT cut (BDT5), 7-variable BDT cut (BDT7), and the final selection. Lines are to guide the eye.

TABLE I. The number of events in 281 days are shown after application of all selection criteria. N^{obs} denotes the number of observed data events. An average of the Bartol and Honda event rates is also shown. The neutrino simulations have statistical uncertainties of less than 2% while the atmospheric muon MC has a statistical uncertainty of 45%.

Type	Signal			Background		MC Sum	N^{obs}
	ν_e NC	ν_e CC	ν_μ NC	ν_μ CC	atm. μ		
Bartol	26	290	267	403	147	1134	-
Honda	19	227	245	368	147	1007	-
Average	23	259	256	385	147	1070	-
Data	-	-	-	-	-	-	1029

that half of the cascades are produced by ν_e (primarily CC interactions) and half are ν_μ NC events. The final event rates are shown in Table I. For atmospheric muons, the overall rejection is 4×10^8 with respect to the total IceCube trigger rate. However, the limited size of the simulated atmospheric muon sample which could be produced with the available computational resources results in a large statistical uncertainty in this background.

The largest systematic uncertainty in the signal prediction comes from the light detection efficiency in a DOM *in situ*. Varying the efficiency by 10% in the simulations, the predicted atmospheric neutrino rate changes by 11% for ν_μ and 10% for ν_e . The same procedure is performed for the atmospheric muons, except at an earlier stage (BDT7) of the analysis to ensure adequate statistics

and gives 30% uncertainty. The systematic uncertainties due to the optical properties of ice are estimated as 8% for atmospheric muons and 6% (2%) for atmospheric ν_μ (ν_e) by comparing final level rates from simulations with two different ice models. With *in situ* calibration light source data at all depths of the detector, the baseline ice model is derived from a global fit to the data obtaining a collection of parameters for scattering and absorption properties [23], while the alternative uses fits to describe the time and amplitude distributions for emitter-receiver pairs [24].

We conservatively estimate the uncertainty in the atmospheric muon rate due to uncertainties in cosmic ray composition by comparing our baseline simulation, based on spectra of individual elements [25] with a proton-only composition model. The comparison is made at the BDT7 stage to ensure sufficient statistics, and shows a rate variation of 25%. Additionally, a 20% uncertainty for the cosmic ray flux normalization and 6% for the seasonal rate variation are included. These are summed in quadrature and give a total of 33% cosmic-ray flux uncertainty. Though large, this cosmic-ray flux uncertainty is smaller than the statistical uncertainty in the atmospheric muon rate due to the limited MC sample, so we use this estimate as the systematic uncertainty. The systematic uncertainty for neutrino-nucleon cross sections is estimated to be 6%. The atmospheric ν_μ flux uncertainties of 9% are obtained by comparing the final event rates with the Honda and Bartol predictions. Neutrino oscillations have a very small effect in this sample (1.8% for ν_μ and 0.1% for ν_e) due to the relatively high energy, $\langle E_\nu^{\text{reco}} \rangle \sim 232$ GeV (see Fig. 3). The ν_τ contribution is estimated to be less than 1% of the data sample assuming standard oscillation parameters [26]. The total systematic uncertainties are 14% (11%) for atmospheric ν_μ (ν_e) and 45% for atmospheric muons, as shown in Table II.

The atmospheric muon background and the atmospheric ν_μ CC background are subtracted from the data. The latter contribution is estimated by averaging the Bartol and Honda atmospheric neutrino predictions. Half the difference is included in the systematic uncertainties. We observe an excess of cascade events,

$$N_{\text{cascade}} = 496 \pm 66(\text{stat.}) \pm 88(\text{syst.}),$$

where the total statistical uncertainty includes statistical uncertainties of the two subtracted background components, and the total systematic uncertainty is a sum in quadrature of the ν_μ CC systematic uncertainties and the atmospheric muon systematic uncertainties. Since part of the systematic uncertainties does not come from the final level comparison, we conservatively do not consider the correlations among the systematic uncertainties. The cascade signal has a significance of 4.5 standard deviations. We estimate based on simulations that $240 \pm 66(\text{stat.}) \pm 109(\text{syst.})$ of the cascades are produced

TABLE II. Systematic uncertainties.

Source of uncertainties	atm. μ	atm. ν_μ	atm. ν_e
Ice properties	8%	6%	2%
DOM efficiency	30%	11%	10%
Cosmic-ray flux	33%	-	-
ν -nucleon cross section	-	6%	6%
Sum	45%	14%	11%

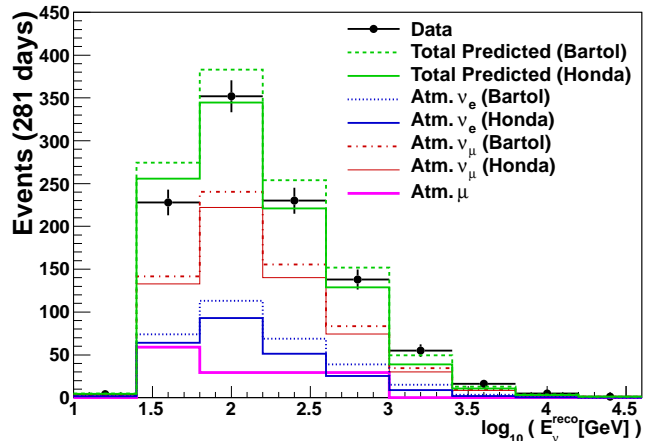


FIG. 3. (Color online) The event rate as a function of the reconstructed cascade energy. The sum of all MC expectations (green) is consistent with 281 days of data rate. The dotted lines show the Bartol prediction while the solid lines indicate Honda predictions for the atmospheric neutrinos. Data are shown with statistical errors. Systematic uncertainties (Table II) are omitted for clarity.

by ν_e . The data appear consistent with Honda model, and slightly below Bartol model which predicts 127 more neutrino events in total. The lower rate prediction from the Honda model, especially in ν_e , is due to the different treatment of kaon production in the atmosphere [27], and is shown in Table I. Both Honda and Bartol estimate roughly 15% uncertainties in the atmospheric ν_e flux at 100 GeV rising to 25% at 1 TeV [11, 12, 19].

Likelihood reconstructions are performed on every event in the final sample, simultaneously fitting a cascade hypothesis for deposited energy and vertex position and time. A vertex resolution of 9 m and an energy resolution of 0.12 in $\log_{10}(E/\text{GeV})$ are obtained. The absolute energy scale uncertainty is found to be 0.1 in $\log_{10}(E/\text{GeV})$. Using the energy reconstruction in Fig. 3 (rebinned to get sufficient statistics and reasonable uncertainties in each bin), we subtract the atmospheric muon and the atmospheric ν_μ CC and ν_μ NC to estimate the ν_e excess. The ν_e excess is converted into flux by normalizing to the expected number of events from an average of the Bartol and Honda fluxes. In each bin, the horizontal bar indicates the bin width. The marker is placed at a point representing the average reconstructed energy of the contributing events. The vertical error bars include

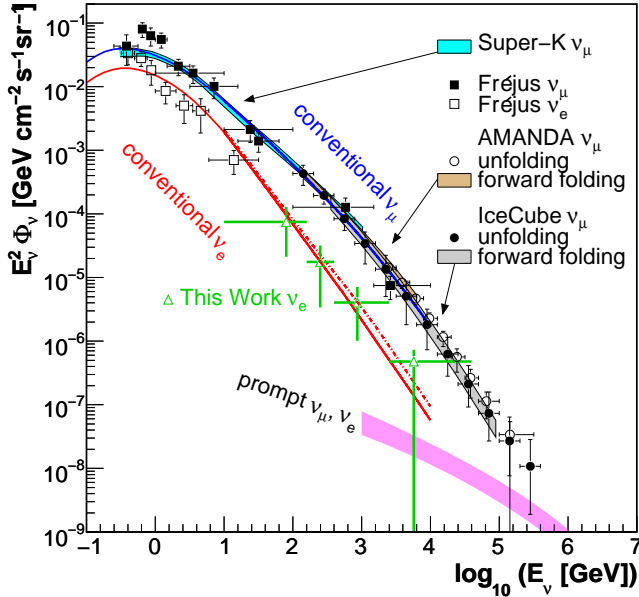


FIG. 4. (Color online) The electron neutrino spectrum (green open triangles). The conventional ν_e (red line) and ν_μ (blue line) from Honda, ν_e (red dotted line) from Bartol and charm-induced neutrinos (magenta band) [28] are shown. Previous measurements from Super-K [29], Fréjus [4], AMANDA [30, 31] and IceCube [1, 32] are also shown.

TABLE III. The $E_\nu^2 \Phi_\nu$ flux. E_ν is in GeV.

$\log_{10} E_\nu^{\min} - \log_{10} E_\nu^{\max}$	$\langle E_\nu \rangle$	$E_\nu^2 \Phi_\nu (\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1})$
1.0 – 2.2	80	$(7.5 \pm 5.4) \times 10^{-5}$
2.2 – 2.6	251	$(1.8 \pm 1.4) \times 10^{-5}$
2.6 – 3.4	865	$(4.1 \pm 3.1) \times 10^{-6}$
3.4 – 4.6	5753	$4.8^{+2.6}_{-4.8} \times 10^{-7}$

the statistical and systematic uncertainties (see Fig. 4 and Table III).

In conclusion, we have observed atmospheric neutrino-induced cascades, produced by ν_e CC interactions and NC interactions of all flavors in IceCube. The atmospheric ν_e flux in the energy range between 80 GeV and 6 TeV is consistent with current models of the atmospheric neutrino flux. Future work will reduce the statistical and systematic uncertainties and allow the flux to be measured more precisely. The techniques used to identify neutrinos interacting within the DeepCore volume and veto atmospheric muons originating outside the detector can be applied to studies of neutrino oscillations and searches for low energy neutrinos from astrophysical sources or from dark matter annihilation or decay.

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